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PERFORMANCE EVALUATION OF MILITARY ENGINE AND GEAR OILS IN FRICTION AND WEAR DEVICES

FINAL REPORT
BFLRF No. 256

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For this program, eight lubricants were selected from three military lubricant specifications: three lubricants from MIL-L-2105C multipurpose gear lubricants, grades 75W, 80W-90, and 85W-140; three reference grade MIL-L-2104D tactical engine lubricants, grades 10W, 40, and 15W-40; one grade 0W-20 MIL-L-46167A Arctic engine lubricant; and one grade CD/50 lubricant that met the MIL-L-2104C specification. The lubricants were tested and evaluated under a wide range of lubrication environments using five friction-and-wear test devices. The results were analyzed by using a one-way analysis of variance (ANOVA) procedure.

Also, a Tukey multiple comparison test was used to compare pairs of means among the gear and engine lubricants within a given test method. Lubricants were determined that had significantly different means from the other lubricants. Rankings based on the order of the average response (Cont'd)

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from the statistical analysis were compared to the rankings determined from the test procedure performance results. Also, a linear regression analysis was able to correlate the results of two of the test methods with 89-percent accuracy, but the analysis could not predict the results of the other three tests with sufficient accuracy. The best overall performance with the least trade-offs was selected. This lubricant was a grade CD/50, MIL-L-2104C tactical engine lubricant equivalent and could be used as a gear lubricant.

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FOREWORD

This work was performed at the Belvoir Fuels and Lubricants Research Facility (BFLRF) located at Southwest Research Institute (SwRI), San Antonio, TX, under Contract No. DAAK70-87-C-0029, for the period 28 August 1987 through 28 August 1988. Work was funded by the U.S. Army Belvoir Research, Development and Engineering Center, Ft. Belvoir, VA, with Dr. Madeline Swann (STRBE-VFF) serving as contracting officer's representative.

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I. INTRODUCTION/BACKGROUND

The Army has historically been a proponent of "multipurpose" or "universal" engine and/or power-train lubricants. The Army's advocacy for a multipurpose lubricant has been primarily to minimize both logistic requirements and the possibility of maintenance mistakes in the field. The elaborate logistics system in the modern military operations requires flexibility. Currently, this logistics system provides many different lubricants that must meet many different specifications, and the lubricants must be transported and stored the world over. Basically, this situation is brought about by the different requirements, both within and between groups of engines and power-transmitting equipment. Although the lubrication requirements of a piston, CI and SI types; of standard manual clash-type transmissions; of automatic and power-shift transmissions; hydraulically operated power-assist equipment (i.e., pumps, winches, etc.); transfer cases; and different axle drives are in some ways similar, they are also, in many ways, very different. When other classes of lubrication are included, e.g., ground turbine engines, wet brakes, and metal-to-metal traction drives, additional performance requirements are introduced. Traditionally, the Army has used various automotive specification products in as many applications as possible and would accept some performance trade-off in favor of reduced logistics. It is known that a lubricant formulation can be tailored to meet specific requirements. However, as the list of requirements grows, the lubricant becomes a "multipurpose" lubricant, and experience shows that some performance penalty must be accepted in one area to obtain a performance benefit in another area.

For years, the Army has used a given type of lubricant in more than one application. One example is the use of OE-30 in engine crankcases and in certain standard manual clash-type transmissions and transfer cases. Another example is the use of OE-10 and OEA 0W-20 in power-steering pumps, hydraulic systems, automatic and power-shift transmissions, and in engine crankcases under certain ambient temperature. Prior to the development of hypoid axles and during the early days of the automatic transmission and moderate output SI engines (prior to WW II), it was common to find a straight mineral-based lubricant used throughout certain automotive power trains. With the introduction of the hypoid gear system, multipurpose power transmission, widespread use of diesel engines, and higher output SI engines, the development of universal power-train lubrication technology has fallen down because of the wide differences in technical requirements. Numerous publications discuss multipurpose gear oils, multipurpose

tractor oils, heavy-duty power-transmission oils, and multipurpose engine oils, but for one technical reason or another, like temperature, type service, extreme pressure or controlled frictional requirements, the military has not been able to use one lubricant for all ground vehicle, and power-train applications. Throughout the years of automotive lubricant development, there has been a need for a multipurpose or universal oil that could be used in all systems and in all environments. This study of engine oils (MIL-L-2104D and MIL-L-46167A) compared to gear oils (MIL-L-2105C) should contribute to the complex technology of universal lubricant development.

II. OBJECTIVE

The objective of this program was to define the lubricant qualities of selected military engine and gear lubricants under a wide range of lubrication environments using different friction and wear test devices and then attempt to show correlation between the results of the different test devices. Dependent on these results, these data could be used to determine which engine oils can be substituted for gear lubricants.

III. TEST DETAILS

A. Test Lubricants

For this study, eight lubricants were selected for evaluation from three military lubricant specifications. These lubricants are listed in TABLE 1.

For this program, three lubricants were selected from the MIL-L-2105C (1)* Multipurpose Lubricating Gear Oil Qualified Products List (QPL), grades 75W, 80W-90, and 85W-140. These oils are intended for automotive gear units such as differentials and manual transmissions, heavy-duty industrial-type enclosed gear units, steering gears, and fluid-lubricated universal joints of automotive ground equipment when ambient temperatures are above -54°C (-65°F).

* Underscored numbers in parentheses refer to the list of references at the end of this report.

TABLE 1. Test Lubricants

Lube No.	BFLRF Code	Specification/Description
1	AL-16780-L	MIL-L-2105C; Grade 75W, MG-415
2	AL-16781-L	MIL-L-2105C; Grade 80W-90, MG-800
3	AL-16782-L	MIL-L-2105C; Grade 85W-140, MG-801
4	AL-14081-L	MIL-L-2104D; Grade 10W, MC-2878 Ref. Oil
5	AL-15478-L	MIL-L-2104D; Grade 40, MC-2879 Ref. Oil
6	AL-16215-L	MIL-L-2104D; Grade 15W-40, MC-2777 Ref. Oil
7	AL-16675-L	MIL-L-46167A; Grade 0W-20, ME-20
8	AL-16740-L	MIL-L-2104C Equivalent; Grade CD/50

Three reference grade MIL-L-2104D (2) tactical engine lubricating oils were selected from the QPL, grades 10W, 40, and 15W-40. The engine oils are intended for the crankcase lubrication of reciprocating internal combustion engines used in all types of military tactical equipment, including electric generators, engineer/construction and material-handling equipment, and for the crankcase lubrication of high-speed, high-output, super/turbocharged diesel engines used in all ground equipment at ambient temperatures above -25°C (-13°F). These oils are also used in power transmissions, engineer/commercial construction and material-handling equipment hydraulic systems, and in nonhypoid gearbox applications in tactical and combat ground equipment.

One lubricant, grade 0W-20, was selected from the MIL-L-46167A (3) Arctic engine lubricating oil (OPL). This oil is suitable for crankcase lubrication of gasoline and diesel engines in all types of ground equipment including electric generators, engineer/construction and material-handling equipment. The oil is intended for use under all conditions of service when ambient temperatures are in the range of 4°C to -54°C (40°F to -65°F). In addition, the oil is for use in arctic regions as an all-weather (year-round) power-transmission fluid for military tactical and combat ground equipment.

In addition, a grade 50 lubricant, without a viscosity index (VI) improver, was selected. This grade is no longer listed in the MIL-L-2104D specification. Therefore, a commercial SAE 50 API/SAE performance classification CD was selected that also met the MIL-L-2104C (4) specification.

Each lubricant was conducted in duplicate with each of the five following test methods.

B. Friction-and-Wear Tests

The four ASTM tests selected for this work were conducted in accordance with the 1987 Annual Book of ASTM Standards, Section 5, Volumes 05.01, 05.02, and 05.03 Petroleum Products and Lubricants. The Caterpillar TO-2 friction retention test was monitored by Caterpillar Company personnel and was conducted in accordance with its specification. This same test has been adopted by an ASTM subcommittee and is listed in the 1988 Annual Book of ASTM Standards as ASTM D 4736. These tests are used in numerous manufacturer specifications to qualify lubricants to be used in their equipment. These lubricants include extreme pressure gear, way, hydraulic, hydraulic machine, antiwear hydraulic, turbine, power-shift transmission and engine lubricants. The five friction, load-carrying, and wear tests that were conducted are briefly described below:

1. ASTM D 2882, Volume 05.02, Standard Test Method for Indicating the Wear Characteristics of Petroleum and Nonpetroleum Hydraulic Fluids in a Constant Volume Vane Pump

This method uses a high-pressure constant volume vane pump test procedure for indicating the wear characteristics of hydraulic fluids operating in a constant volume. The equipment uses a rotary vane pump, replacement cartridge-type (Vickers 104C or 105C rated at 7.5 gal./min (28.4 liters/min) flow). The pump is operated at 1200 rpm, with 2,000 psi using a lubricant temperature of 150°F (65.6°C) or 175°F (79.4°C), depending on the fluid viscosity at 104°F (40°C) for a period of 100 hours. The results are obtained as pump wear total weight loss, consisting of cam ring and vanes weight loss, during the test. Excessive wear in vane pumps could lead to a malfunction in the hydraulic systems under critical applications.

2. ASTM D 4172, Volume 05.03, Standard Test Method for Wear Preventive Characteristics of Lubricating Fluid (Four-Ball) Method

This method covers a procedure for preparing a preliminary evaluation of the antiwear properties of a fluid lubricant by means of a four-ball wear test machine manufactured by Faville-LeVally Corp. The test is conducted using a force of 15 kgf (147N) or 40 kgf (392N) at 167°C (75°C) using 1200 rpm for 60 minutes. Three balls are clamped in place

and another ball rotates in the pocket formed by the three stationary balls. A scar is formed on each of the stationary balls. Lubricants are compared by using the average size of the scar diameters worn on the three lower clamped balls.

3. ASTM D 2782, Volume 05.02, Standard Method for Measurement of Extreme Pressure Properties of Lubricating Fluids (Timken Method)

This method, which covers the load-carrying capacity of lubricating fluids by means of the Timken extreme pressure tester, manufactured by Timken Ltd. This method is used widely for specification purposes and is used to differentiate among lubricants having low, medium, or high levels of extreme pressure characteristics. Two determinations are made: 1) the minimum load (score value) that will rupture the lubricant film being tested between the rotating cup and the stationary block and cause scoring or seizure, and 2) the maximum load (OK value) at which the rotating cup will not rupture the lubricant film or cause scoring or seizure.

4. ASTM D 1947, Volume 05.01, Standard Test Method for Load-Carrying Capacity of Petroleum Oil and Synthetic Fluid Gear Lubricants (Ryder Gear)

This test method covers the determination of the load-carrying capacity of petroleum oil and synthetic fluid gear lubricants. It does, however, exclude worm and hypoid gear applications. The oil is evaluated in a standard WADD gear machine using standard Ryder AMS-6260 steel gears. The tester is operated under controlled conditions specified in the test method. The test gears are loaded first to 5 psig (34.5 k N/m^2 gauge) load oil pressure, and then at successive increments of 5 psi. The duration of each loading period is 10 minutes $\pm$ 5 seconds. The amount of tooth-face scuffing occurring at each load increment is measured. The percentage of tooth-face scuffing is plotted against the load to determine the load-carrying capacity of the test oil.

5. Caterpillar Engineering Specification No. TO-2, Friction Retention Test (ASTM D 4736)

This test, monitored by Caterpillar for TO-2 qualification, makes use of the SAE No. 2 friction test machine, which has the clutch plates submerged in the test fluid. The standard SAE No. 2 friction machine is modified to provide oil flow through the clutch pack to an external oil reservoir and oil coolers. Also, the clutch pack lockup time is

controlled. Bronze-on-steel friction material is used. The results compare favorably with the full-scale Caterpillar power-shift transmissions, and are reported as maximum slip-time percent increase and maximum wear of the bronze disc and steel plates for 15,000 test cycles. This test is used in the MIL-L-2104D Tactical Engine Oil specification.

IV. DISCUSSION OF RESULTS

A. Test Results

The compiled data from the five tests were conducted in duplicate on each of the eight lubricants and are reported in TABLE 2. Also, listed in TABLE 2 are the ASTM D 445 viscosity results. These ASTM D 445 tests were conducted on the eight lubricants to verify the viscosity of each lubricant. The results in TABLE 2 are discussed in the subsequent paragraphs and are included with a performance ranking of the eight lubricants:

1. ASTM D 2882 Test Method for Indicating the Wear Characteristics of Hydraulic Fluids in a Constant Volume Vane Pump (Vickers)

The results from this test are reported as total weight loss in mg. The values are obtained by totaling the weight loss result from the cam ring and the twelve vanes (see TABLE 2). The total weight loss standard recommended by industry and the military is 50 mg. All eight lubricants recorded a total weight loss of less than 50 mg and can be seen graphically in Fig. 1. The grade 75W and 85W-140 gear lubricants, along with grades 40 and CD/50 engine/transmission lubricants, recorded average total weight losses of less than 15 mg. The 80W-90 grade gear lubricant and the 10W, 15W-40, and 0W-20 grade engine/transmission lubricants recorded total weight losses of more than 15 mg, but less than the suggested 50-mg limit. The grade 85W-140 gear lubricant recorded the best results, but none of the eight lubricants should have any wear problems as a hydraulic fluid. From the limited data, the D 2882 vane pump wear test does not appear to show any difference between the gear and engine/transmission lubricants.

TABLE 2. Gear and Engine/Transmission Lubricants Test Results

Lubricant No.	1	2	3	4	5	6	7	8
BFLRF Code	AL-16780-L	AL-16781-L	AL-16782-L	AL-14081-L	AL-15478-L	AL-16215-L	AL-16675-L	AL-16740-L
Grade	75W	80W-90	85W-140	10W	40	15W-40	0W-20	CD/50
Specification		MIL-L-2105C			MIL-L-2104D		MIL-L-46167A	MIL-L-2104C Equivalent
Test Method								
1. ASTM D 2882, Vickers Vane Pump Wear								
Ring, wt loss, mg	2.8 (5.2)*	19.3 (17.7)	2.6 (2.7)	26.0 (18.8)	15.9 (1.7)	28.7 (40.9)	12.7 (9.6)	5.7 (4.9)
Vane, wt loss, mg	1.7 (3.1)	6.5 (7.2)	1.0 (1.0)	7.4 (16.3)	3.4 (4.8)	8.7 (7.9)	12.8 (7.0)	1.3 (1.0)
Total, wt loss, mg	4.5 (8.3)	25.8 (24.9)	3.6 (3.7)	33.4 (35.1)	19.3 (6.5)	37.4 (48.8)	25.5 (16.6)	7.0 (5.9)
2. ASTM D 4172, Four-Ball Wear Characteristics								
Avg Scar Diameter, mm	0.41 (0.42)	0.34 (0.35)	0.36 (0.37)	0.42 (0.44)	0.41 (0.42)	0.41 (0.43)	0.35 (0.36)	0.40 (0.41)
3. ASTM D 2782, Timken Extreme Pressure Properties								
OK Load Value, lb	65 (70)	75 (75)	85 (85)	12 (24)	24 (24)	21 (21)	21 (24)	40 (40)
4. ASTM D 1947, Load-Carrying Ryder Gears								
Load-Carrying Capacity, N/cm	8511 (8511)	8511 (8511)	8511 (8511)	4860 (5130)	6146 (5928)	6611 (5910)	4684 (4824)	6690 (6366)
5. ASTM D 4736, Caterpillar TO-2 Friction								
Percent Change**	35.91 (34.08)	24.02 (9.68)	***	36.26 (21.11)	21.91 (20.11)	21.79 (24.58)	11.66 (10.53)	3.80 (27.49)
4-Bronze Discs, avg wear, 250 µm	35.6 (61.4)	50.8 (+264.2)	***	45.7 (50.8)	33.0 (63.5)	38.1 (43.2)	152.4 (144.8)	228.2 (71.1)
5-Steel plates, avg wear, 100 µm	40.6 (38.4)	61.0 (106.7)	***	38.1 (43.2)	43.2 (55.9)	43.2 (27.9)	50.8 (63.5)	129.5 (45.7)
Total Wear, 350 µm, max	76.2 (99.8)	111.8 (+157.5)	***	83.8 (94.0)	76.2 (119.4)	81.3 (71.1)	203.2 (208.3)	358.2 (116.8)
Test Cycles, 15,000 min	1,162 (1,050)	580 (3,000)	***	4,000 (4,000)	15,000 (15,000)	15,000 (4,500)	15,000 (15,000)	15,000 (15,000)
ASTM D 445, Kinematic Viscosity								
40°C, cSt	31.95	121.48	318.97	39.59	138.72	97.98	26.84	191.22
100°C, cSt	5.65	13.78	24.96	6.23	14.18	13.13	5.92	17.62

* Duplicate test results.
** 20-percent max change for 10W, 75W, and 0W-20.
15-percent max change for 80W-90, 85W-140, 40, 15W-40, and CD/50.
*** Failed to exceed the 200-cycle break-in.

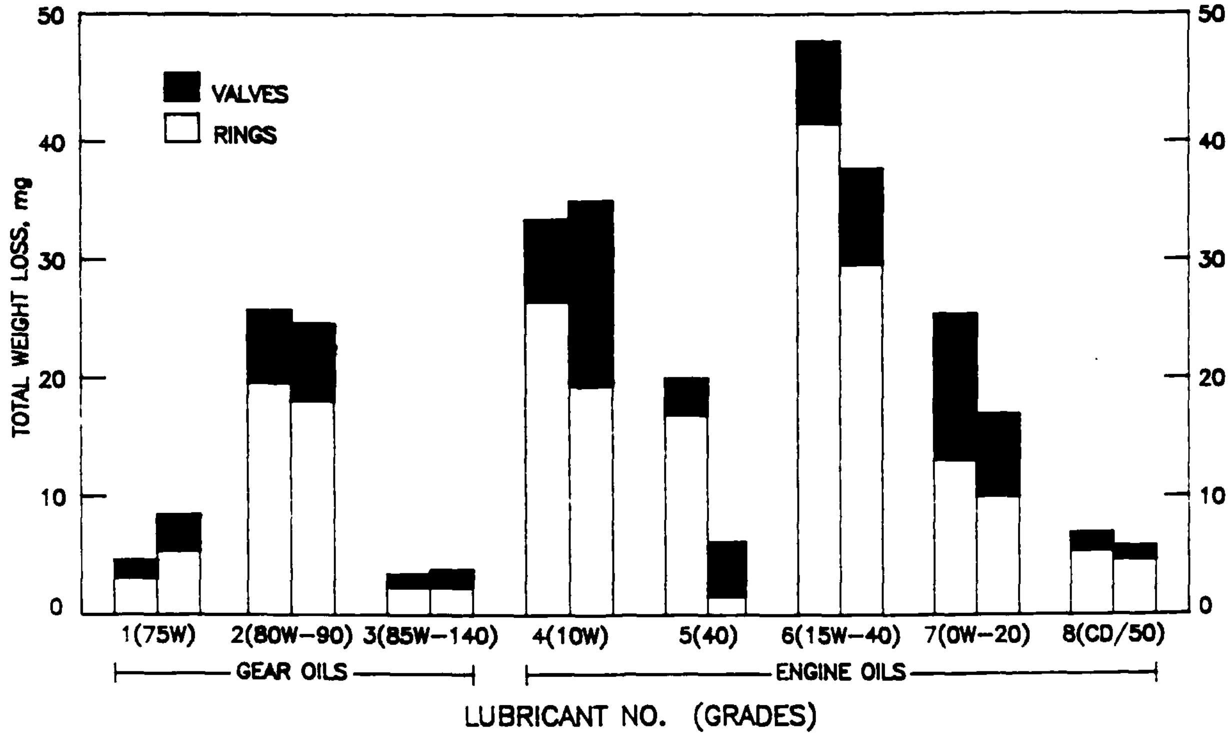

Figure 1. Duplicate results of ASTM D 2882 Vickers vane pump wear test

2. ASTM D 4172 Test Method for Wear Preventive Characteristics of Lubricating Fluids (Four-Ball)

This test method is used as a preliminary evaluation of antiwear properties of a fluid lubricant. The results are reported in TABLE 2 as the average of the scar on the three stationary balls. The results show that the lubricants fall in two separate wear level groups. The 80W-90 and the 85W-140 grade gear lubricants along with the 0W-20 grade Arctic engine/transmission lubricant are grouped showing the best antiwear characteristics as shown graphically in Fig. 2. The grade 75W gear lubricant and the grades 10W, 40, 15W-40, and CD/50 engine/transmission lubricants were grouped at a higher wear level. From this limited data, the testing does not appear to group the lubricants in any particular specification.

3. ASTM D 2782 Test Method for Extreme Pressure Properties of Lubricating Fluids (Timken Method)

This test covers the load-carrying capacity of lubricating fluids and differentiates among lubricants having low, medium, and high levels of extreme pressure characteristics.

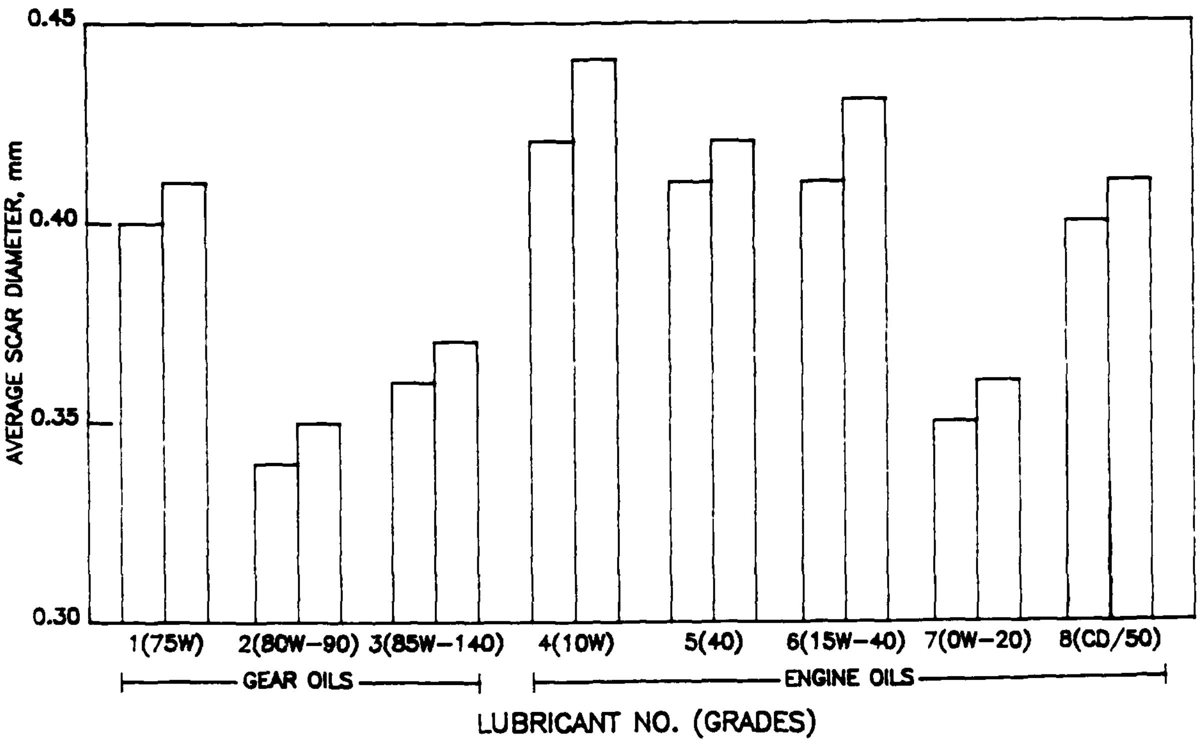

Figure 2. Duplicate results of ASTM D 4172 four-ball test

When the data are reported at loads below 30 lb, there is a 3-lb difference between the score value and the OK load value. Above 30 lb, there is a 5-lb difference between the score and OK load values. The OK load value is shown in TABLE 2. When these data are looked at graphically (Fig. 3), the data appear to fall into three pressure levels. The best and highest pressure level of OK load values are recorded by the grades 75W, 80W-90, and 85W-140 gear lubricants in the 65- to 85-lb band. The medium load level was recorded by the CD/50 grade engine/transmission lubricant at 40 lb. The lowest level of OK load values are recorded by the grades 10W, 40, 15W-40, and 0W-20 engine/transmission lubricants in the 12-to 24-lb band. This method appears to group the lubricants into gear and engine/transmission lubricant categories.

4. ASTM D 1947 Test Method for Load-Carrying Capacity of Fluid Gear Lubricants (Ryder Gear)

The average load-carrying capacity results are shown in TABLE 2. A summary of the individual load-carrying capacity determinations and the average standard deviation and 95-percent confidence intervals were calculated for each lubricant and are presented in TABLE 3. When the 95-percent confidence intervals are taken into consideration, the

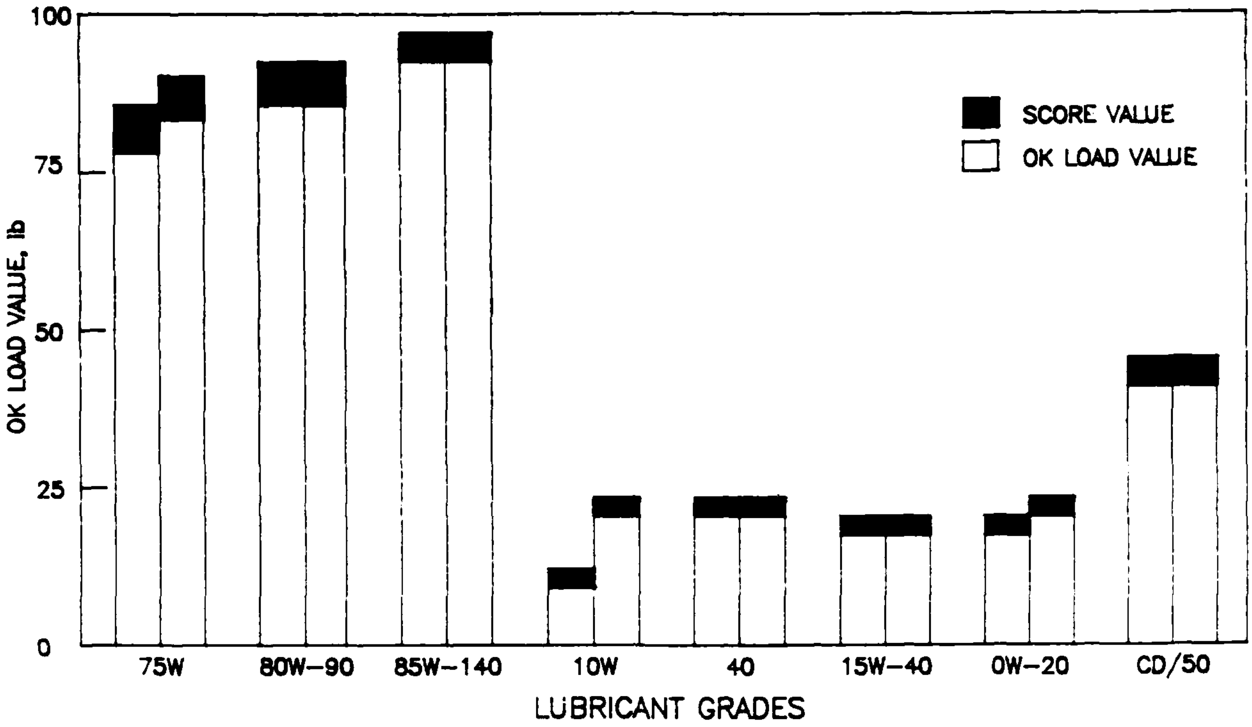

Figure 3. Duplicate results of Timken extreme pressure test

eight lubricants can be shown to fall into three general groupings, as shown in Fig. 4. The first group contains grades 10W and 0W-20 engine/transmission lubricants. These lubricants cannot be adequately distinguished from each other with the small amount of data available, since their 95-percent confidence intervals overlap. The second group, composed of lubricant grades 15W-40, 40, and CD/50 engine/transmission lubricants, does not overlap the confidence intervals of the third group of lubricants. This third group had load-carrying capacities greater than the 8511 N/cm (4860 lb/in.) but incalculable confidence intervals. From these data, the method appears to distinguish between lighter grade Arctic-type 10W and 0W-20 engine/transmission lubricants, the heavier grade 40, 15W-40, and CD/50 engine/transmission lubricants and the hypoid-type grades 75W, 80W-90, and 85W-140 gear lubricants. From this limited data, the method does appear to be successful in separating gear and engine lubricants but cannot distinguish within each specification class.

TABLE 3. Summary of Gear Load-Carrying Capacity Determinations for Eight Lubricants Using the WADD Gear Machine in Accordance With ASTM Method D-1947*

Lube No.	BFLRF Code	Load-Carrying Capacity, N/cm (lb/in.) A Side		B Side	Test No.
1	AL-16780-L	>8511 (>4860)		>8511 (>4860)	5039
		>8586 (4960)		>8511 (>4860)	5048
	Avg		>8511 (>4860)		
	Std. Dev.		--		
2	AL-16781-L	>8511 (>4860)		>8511 (>4860)	5033
		>8511 (>4860)		>8511 (>4860)	5045
	Avg		>8511 (>4860)		
	Std. Dev.		--		
3	AL-16782-L	>8511 (>4860)		>8511 (>4860)	5034
		>8511 (>4860)		>8511 (>4860)	5047
	Avg		>8511 (>4860)		
	Std. Dev.		--		
4	AL-14081-L	4518 (2580)		5201 (2970)	5038
		5130 (2930)		5586 (3190)	5043
	Avg		5113 (2920)		
	Std. Dev.		441 (252)		
	95% CI[(a)]		432 (±247)		
5	AL-15478-L	590 (3370)		6392 (3650)	5037
		6164 (3520)		5691 (3250)	5044
	Avg		6042 (3450)		
	Std. Dev.		304 (174)		
	95% CI		298 (±170)		
6	AL-16215-L	6760 (3860)		6462 (3690)	5036
		6339 (3620)		5481 (3130)	5049
	Avg		6260 (3575)		
	Std. Dev.		548 (313)		
	95% CI		538 (±307)		
7	AL-16675-L	4220 (2410)		5148 (2940)	5040
		4711 (2690)		4938 (2820)	5046
	Avg		4754 (2715)		
	Std. Dev.		399 (288)		
	95% CI		390 (±223)		
8	AL-16740-L	6935 (3960)		6444 (3680)	5035
		6619 (3780)		6112 (3490)	5042
	Avg		6531 (3730)		
	Std. Dev.		343 (196)		
	95% CI		336 (±192)		

* Standard AMS-6260 steel test gears used for all tests.

(a) The 95% confidence interval for each respective average load-carrying capacity indicates that the true average value lies somewhere within the indicated interval limits in 95 out of 100 cases.

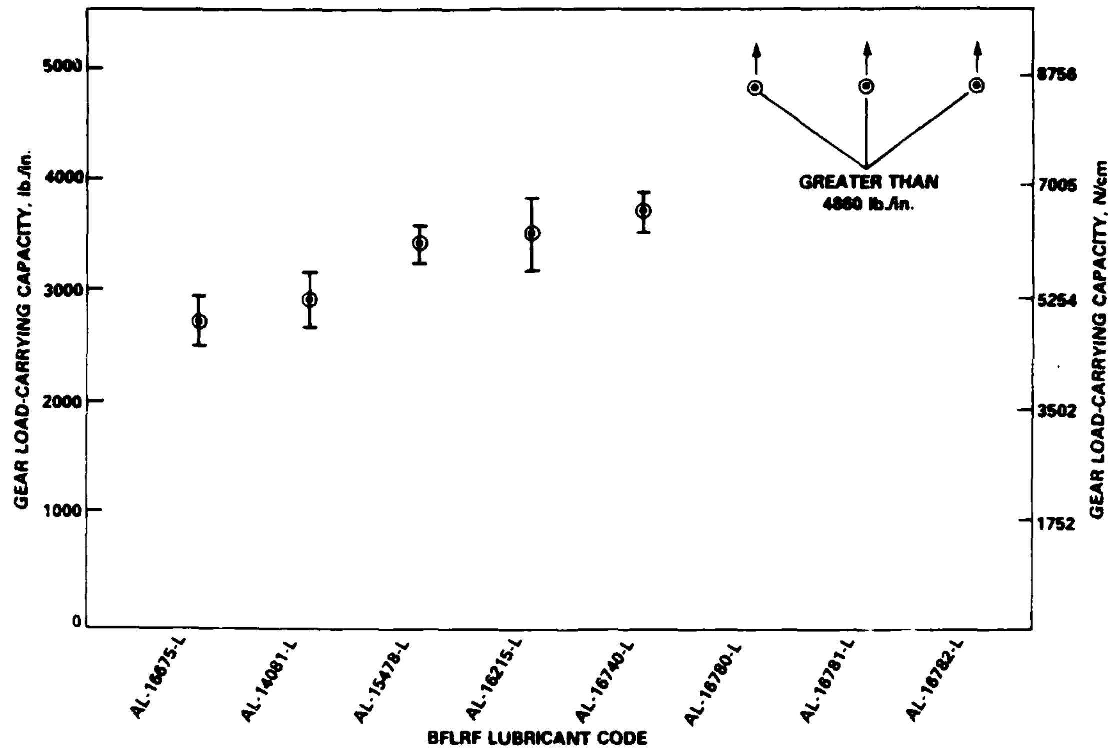

Figure 4. Average load-carrying capacities plotted with respective 95-percent confidence limits included

5. Caterpillar TO-2 Friction Retention Test Method

The TO-2 friction test was conducted on all eight lubricants, and only the grade 0W-20 Arctic engine/transmission lubricant passed (TABLE 2). Four stand reference tests were conducted during the 16 tests, and all met the reference requirements. Reference tests are required only every 12 tests. Additional reference tests were conducted due to problems encountered with the grade 85W-140 gear lubricant testing. The grade 85W-140 gear lubricant could not operate beyond the break-in period. Caterpillar Company was notified of the problem and asked for recommendations. Caterpillar representatives indicated they had no experience with MIL-L-2105C gear lubricants as fluids in the TO-2 friction test. The TO-2 tester is operated at break-in conditions for 200 cycles. The break-in retard cycle conditions are conducted without stopping the drive motor and has a 20-second cycle time. This cycle time includes a 0.7-second clutch apply pressure at 20 psi with the first lockup recorded at 200 cycles. During the 200- to 1000-cycle range, the conditions are adjusted to conduct a stop in 1.80 ± 0.02 seconds with a total cycle time of 15 seconds. Once established, this cyclic procedure is used up to 15,000 cycles. All four tests conducted with the 85W-140 lubricant failed to record a stop in the

prescribed time at the 200-cycle lockup time. A lubricant is deemed unsatisfactory if the stopping time increase calculated from the lowest point on the smooth best-fit curve exceeds 15 percent for SAE grades 40, 15W-40, CD/50, 80W-90, and 85W-140 oils or 20 percent for SAE grades 0W-20, 10W, and 75W oils. As noted, only the 0W-20 Arctic engine oil passed the TO-2 test. Lubricant grades 40, 15W-40, and CD/50 completed the 15,000 cycles, but they failed either the stopping percent increase or showed excessive wear. The failure of these lubricants to pass the TO-2 friction tests was interesting since both MIL-L-2104D and MIL-L-46167A specifications require a lubricant to pass the TO-2 friction test to be listed in the Qualified Products List (QPL). The question is why did these lubricants pass an earlier TO-2 friction test and yet fail the current test? Caterpillar Company representatives were contacted about this problem. These representatives stated that the TO-2 friction test performance had declined for several years due to the steel plates involved in the test. To return the performance to its former level, the surfaces of the steel plates were changed and were fabricated by a new manufacturer. The Caterpillar personnel also reported that many engine oils that had previously passed the TO-2 test during this low-level performance period were failing the TO-2 friction test with the new batch of steel plates. This failure to pass the TO-2 tests should not hinder the outcome of the computer correlation because the lubricants can be compared to each other. The 10W, 75W, 80W-90, and 85W-140 lubricants could not complete the 15,000 cycles or pass the stopping percent increase. The 80W-90 and 85W-140 also had metal transfer on the discs and plates (both bronze-to-steel and steel-to-bronze). When comparing the performance of the MIL-L-2105C gear oils to the MIL-L-2104D engine oils, the engine oils recorded the best TO-2 friction test performance.

Since the four TO-2 test starts did not complete the 15,000 cycles, enough money remained in the program to conduct an X-ray fluorescence (XRF) on the grade 85W-140 lubricant. The results of this XRF analysis were compared to the XRF data on the grade 40 lubricant from previous work (see TABLE 4). The grade 40 lubricant, considered a borderline fail, completed the 15,000 test cycles with low disc and plate wear. However, the lubricant failed the stopping time percent increase with 21 percent; the test limit is a 15-percent increase. The 85W-140 lubricant, as was previously stated, could not complete 200 test cycles.

The XRF analysis comparison with the grade 40 lubricant showed that the 85W-140 gear oil had three times more sulfur, almost twice the phosphorus, and no detectable zinc.

TABLE 4. XRF Analysis

Elemental, ppm	Grade 85W-140 AL-16782-L MIL-L-2105C	Grade 40 AL-15478-L MIL-L-2104D
Sulfur	16,300	5,600
Phosphorus	1,700	1,000
Zinc	--*	1,200

* -- = None Detected.

These initial results indicate that the high-sulfur content may be causing the problem with the bronze and/or steel clutch surfaces.

The data collected from this test program were evaluated numerically to obtain a performance ranking of the eight lubricants. Each test conducted with a particular lubricant was given a rating of 1 = best result down to 8 = worst result. Therefore, the lubricant with the lowest total score was ranked as having the best overall performance of the test lubricants. The best overall performing lubricant was the grade 85W-140 gear lubricant (see TABLE 5), the second ranked lubricant were the grade CD/50 engine/transmission lubricant and the 80W-90 gear lubricant, and the worst ranked was the grade 10W engine/transmission lubricant.

TABLE 5. Rating and Ranking of the Lubricants Performance

	Lubricant Grade and Code Number							
	75W 1	80W-90 2	85W-140 3	10W 4	40 5	15W-40 6	0W-20 7	CD/50 8
ASTM D 2882	3	6	1*	7	4	8	5	2
ASTM D 4172	5	1	3	8	6	7	2	4
ASTM D 2782	3	2	1	8	5	7	6	4
ASTM D 1947	1	1	1	7	6	5	8	4
Caterpillar TO-2	6	7	8	5	2	4	1	3
Rating Total (Smallest No. = Best)	18	17	14	35	23	31	22	17
Performance Ranking	4	2	1	8	6	7	5	2

* 1 = Best; 8 = Worst.

B. Statistical Analysis of Test Results

The determination of correlation coefficients between the defined friction and wear tests is not appropriate for this experimental design. Correlation coefficients cannot be calculated for the gear and engine oils examined in each of the five test methods since there is no inherent, (X, ′) pairing of the specific response data.

The two repeat tests pertormed for each gear and engine oil have provided useful information in determining which gear and engine oils are similar in their mean response under each test method. Each of the measured responses was analyzed using a one-way analysis of variance (ANOVA) procedure. This statistical test compares the average responses of the eight oils for a given test method. If a statistically significant (p 0.05) result was obtained, indicating a difference among the average for the oils, a Tukey multiple comparison test was used to compare pairs of means among the gear and engine oils within a given test method. This latter technique aided in determining which oils had significantly different means from all the other oils.

The ANOVA results indicate significant differences among the oil average responses for the D 2882, D 4172, D 2782, and D 1947 tests. Also, significant differences were obtained for the oil average test cycles for the Caterpillar TO-2 test. These results are summarized in TABLE 6. For each response of every test method, the following information is given:

(i) the p-value associated with the overall ANOVA test
(ii) the oil average responses ordered by size
(iii) an indicator (i.e., asterisks) of groups of oils that are similar in their average responses based on Tukey's test.

Graphical comparisons of the oil average responses are shown in Figs. 5 through 15. Nonoverlapping intervals indicate oil averages that are significantly different at the 0.05 significance level.

TABLE 6. Summary of ANOVA Procedure Results
(Ranked From Best (Left) to Worst (Right))

1. **ASTM D 2882**

(i) Ring (p = 0.003)

Oil	3	1	8	5	7	2	4	6
Avg	2.7	4.0	5.3	8.8	11.2	18.5	22.4	34.8
	a*	a	a	a	a	a	a	
						b	b	b

(ii) Vane (p = 0.023)

Oil	3	8	1	5	2	6	7	4
Avg	1.0	1.2	2.4	4.1	6.9	8.3	9.9	11.9
	a	a	a	a	a	a	a	
		b	b	b	b	b	b	b

(iii) Total Weight Loss (p = 0.0003)

Oil	3	1	8	5	7	2	4	6
Avg	3.7	6.4	6.5	12.9	21.1	25.4	34.3	43.1
	a	a	a	a	a			
		b	b	b	b	b		
					c	c	c	
						d	d	d

2. **ASTM D 4172**

(i) Scar Diameter (p = 0.0001)

Oil	2	7	3	8	1	5	6	4
Avg	0.35	0.36	0.37	0.41	0.42	0.42	0.42	0.43
	a	a	a					
				b	b	b	b	b

3. **ASTM D 2782**

(i) OK Load Value (p = 0.0000)

Oil	3	2	1	8	5	7	6	4
Avg	85.0	75.0	67.5	40.0	24.0	22.5	21.0	18.0
	a	a						
		b	b					
				c				
					d	d	d	d

4. **ASTM D 1947**

(i) Load-Carrying Capacity (p = 0.0000)

Oil	3	2	1	8	6	5	4	7
Avg	8511	8511	8511	6528	6260	6037	4995	4754
	a	a	a					
				b	b	b		
							c	c

5. **Caterpillar TO-2**

(i) Time Increase (p = 0.188)

Oil	7	8	2	5	6	4	1
Avg	11.1	15.6	16.9	21.0	23.2	23.7	35.0
	a	a	a	a	a	a	a

(ii) Bronze - Weight Loss (p = 0.387)

Oil	6	4	5	1	7	8	2
Avg	40.7	48.3	48.3	48.5	148.6	149.7	157.5
	a	a	a	a	a	a	a

(iii) Steel - Weight Loss (p = 0.359)

Oil	6	1	4	5	7	2	8
Avg	35.6	39.5	40.7	49.6	57.2	83.9	87.6
	a	a	a	a	a	a	a

(iv) Total Wear - Weight Loss (p = 0.225)

Oil	6	1	4	5	2	7	8
Avg	76.2	88.0	88.9	97.8	134.7	205.8	237.5
	a	a	a	a	a	a	a

(v) Test Cycles (p = 0.004)

Oil	8	7	5	6	4	2	1
Avg	15000	15000	15000	9750	4000	1790	1106
	a	a	a	a	a		
				b	b	b	b

* Letters indicate groups of oils similar (homogeneous) in average responses based on Tukey's test.

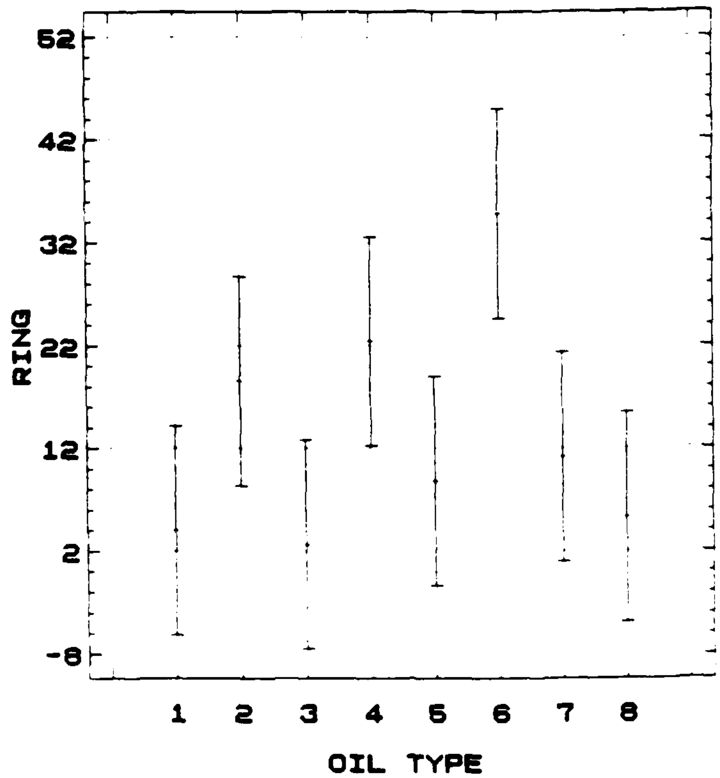

Figure 5. D 2882 ring weight loss—95% Tukey HSD intervals

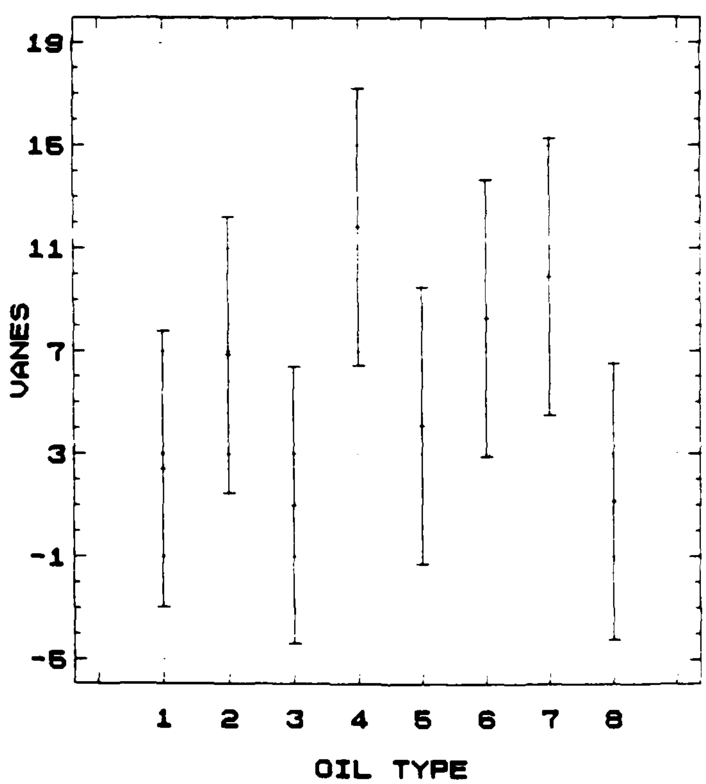

Figure 6. D 2882 vane weight loss—95% Tukey HSD intervals

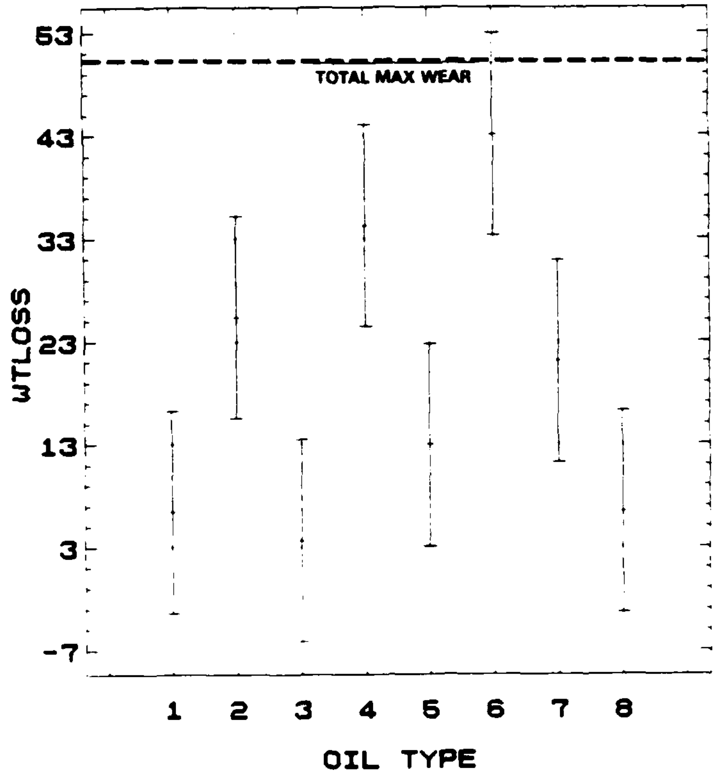

Figure 7. D 2882 total weight loss—95% Tukey HSD intervals

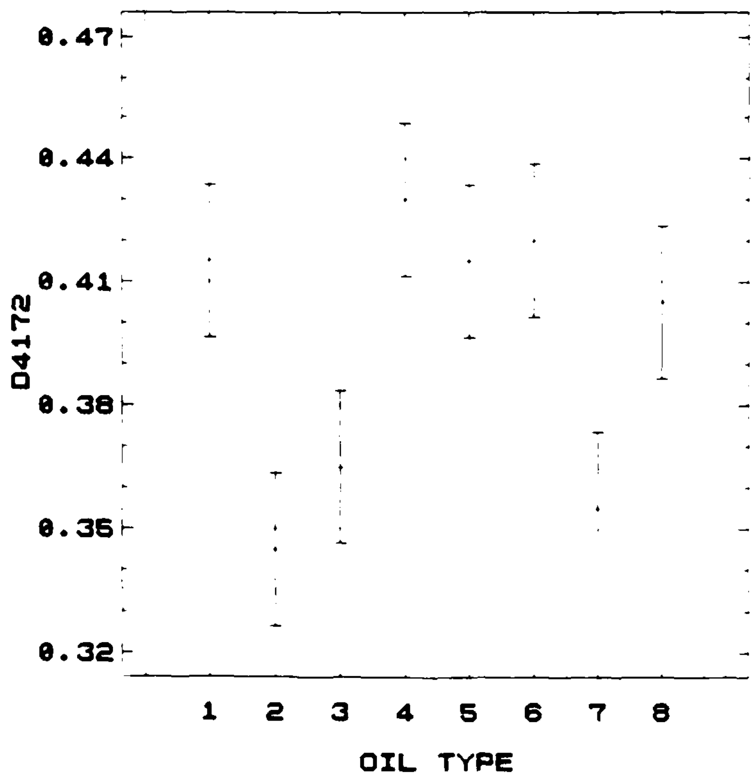

Figure 8. D 4172 scar diameter—95% Tukey HSD intervals

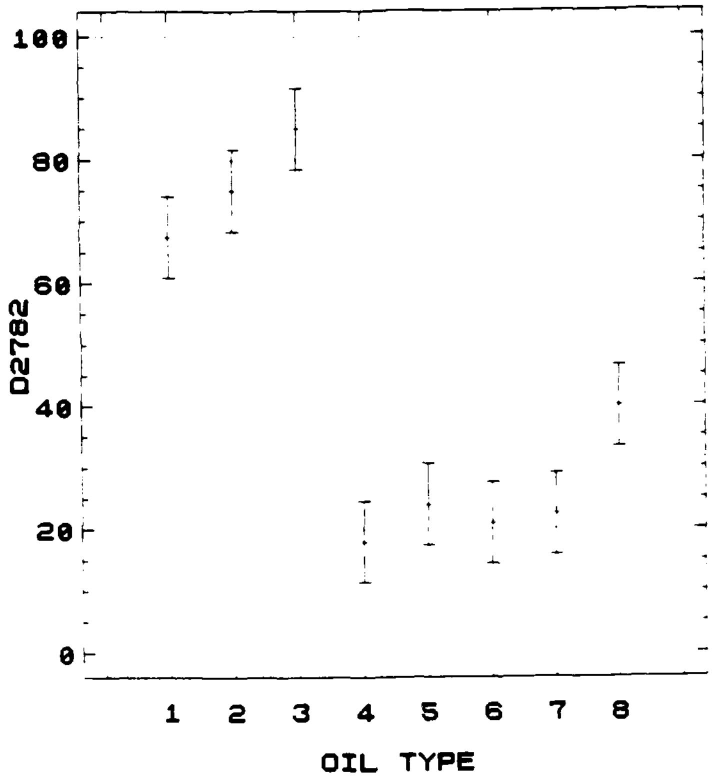

Figure 9. D 2782 OK load value—95% Tukey HSD intervals

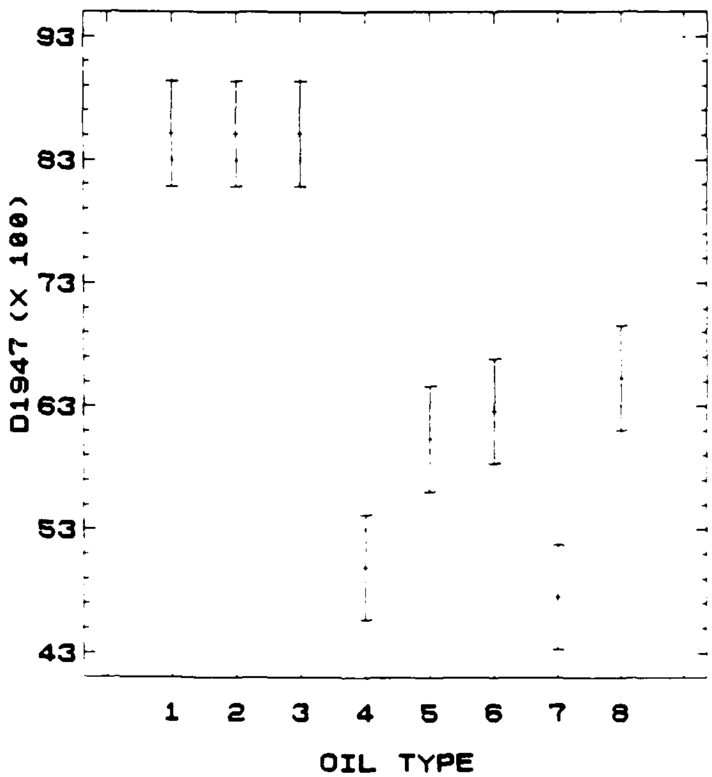

Figure 10. D 1947 load capacity—95% Tukey HSD intervals

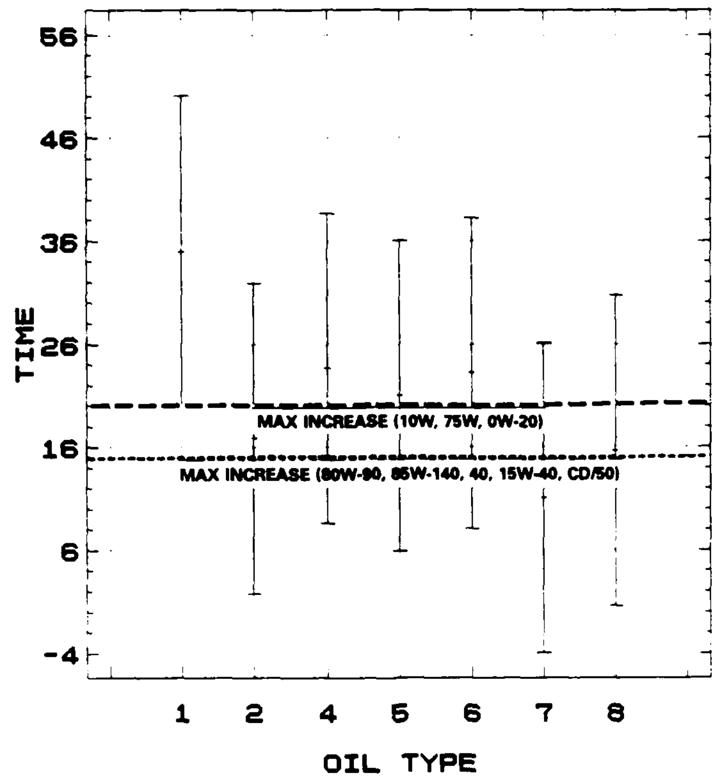

Figure 11. Cat TO-2 time increase--95% Tukey HSD intervals

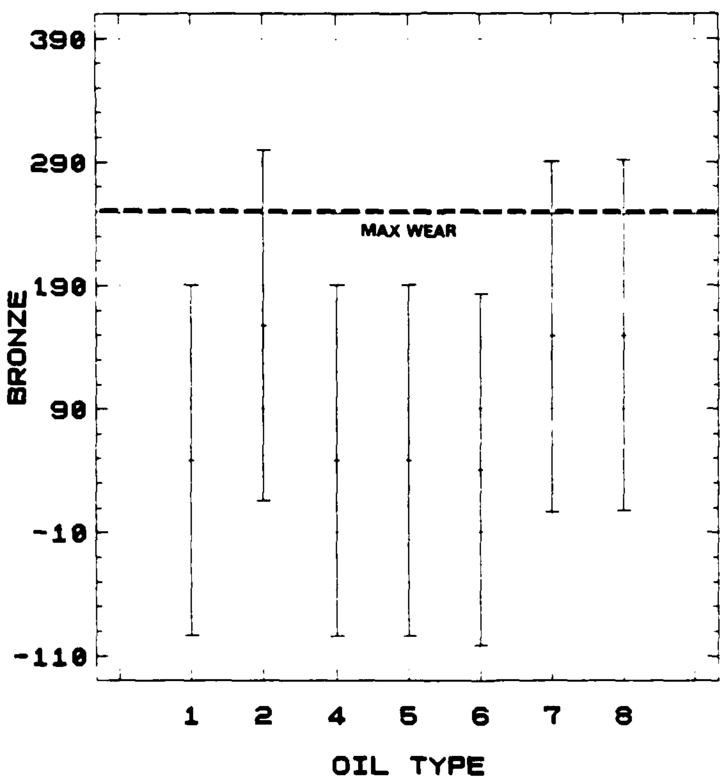

Figure 12. Cat TO-2 bronze wear--95% Tukey HSD intervals

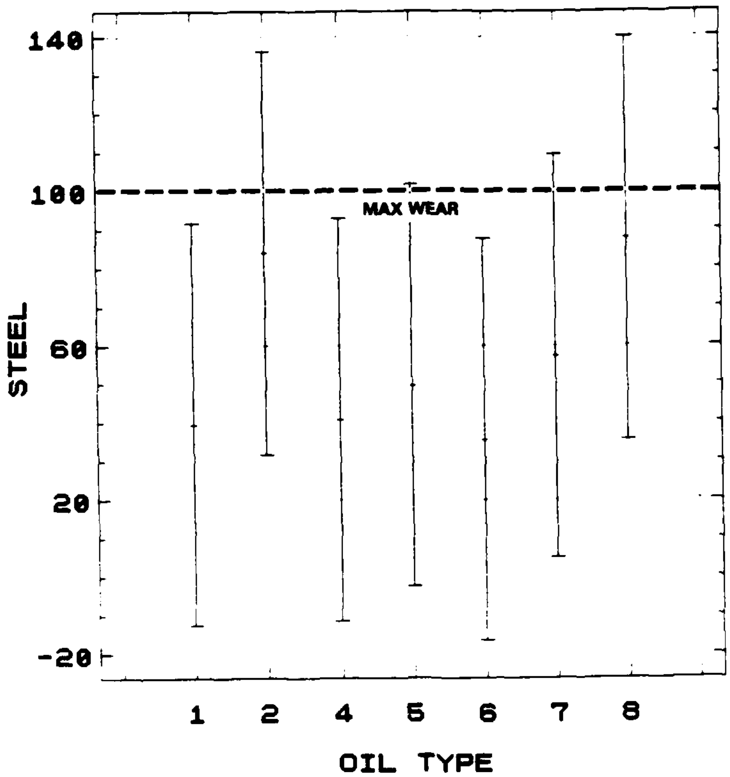

Figure 13. Cat TO-2 steel wear—95% Tukey HSD intervals

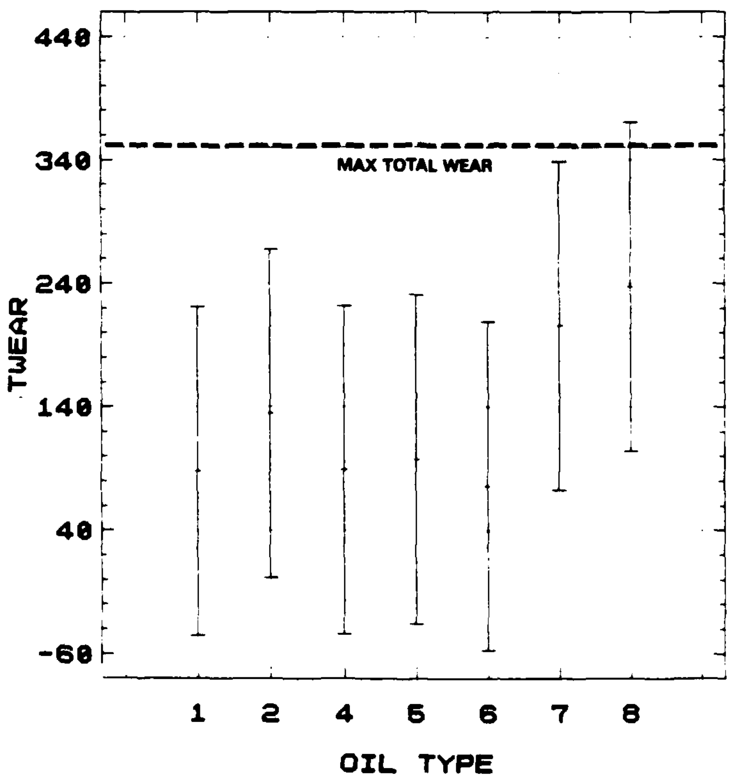

Figure 14. Cat TO-2 total wear—95% Tukey HSD intervals

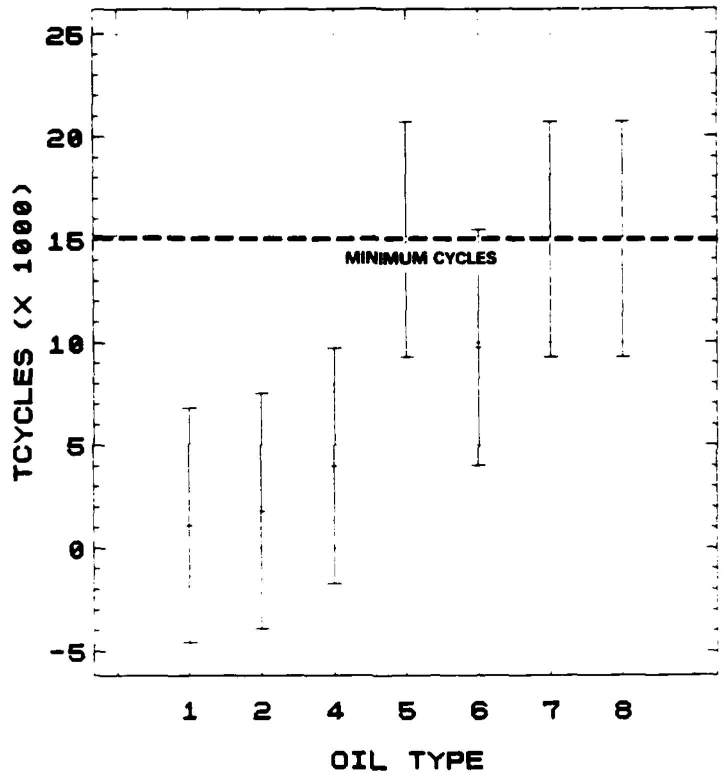

Figure 15. Cat TO-2 test cycles—95% Tukey HSD intervals

1. ASTM D 2882 Test Method for Indicating the Wear Characteristics of Hydraulic Fluids in a Constant Volume Vane Pump (Vickers)

(i) Ring Wear: Lubricant No. 3 (grade 85W-140) gear oil has the lowest average ring wear response while lubricant No. 6 (grade 15W-40) engine lubricant has the highest average ring wear response (TABLE 6, Fig. 5). The eight lubricants fall into two groups based on comparisons of their average responses. Lubricants Nos. 1 through 5, 7, and 8 fall in a group with the lowest average responses and lubricants Nos. 2, 4, and 6 fall in the group with the highest average responses. As noted, lubricants Nos. 2 and 4 are homogeneous to both groups, so that only lubricant No. 6 is significantly different from lubricants Nos. 1, 3, 5, 7, and 8.

(ii) Vane Wear: Lubricant No. 3 (grade 85W-140) gear oil has the lowest average wear response while lubricant No. 4 (grade 10W) engine lubricant has the highest average response (TABLE 6, Fig. 6). The eight lubricants fall into two groups. Lubricants Nos. 3 and 4 have significantly different average responses but the remaining lubricants Nos. 1, 2, and 5 through 8 have similar average responses.

(iii) <u>Total Wear</u>: Lubricant No. 3 (grade 85W-140) gear lubricant has the lowest average response with lubricant No. 6 (grade 15W-40) engine lubricant recording the highest average response (TABLE 6, Fig. 7). The lubricants fall into four groups. Lubricant No. 3 has a significantly lower average than lubricants Nos. 2, 4, and 6. Also, lubricants Nos. 1, 5, and 8 have a significantly lower average than lubricants Nos. 4 and 6.

2. <u>ASTM D 4172 Test Method for Wear Preventive Characteristics of Lubricating Fluids (Four-Ball)</u>

Lubricant No. 2 (grade 80W-90) gear lubricant has the lowest average response with lubricant No. 4 (grade 10W) engine lubricant recording the highest response result (TABLE 6, Fig. 8). Lubricants Nos. 2, 3, and 7 have significantly lower average responses than lubricants Nos. 1, 4, 5, 6, and 8.

3. <u>ASTM D 2782 Test Method for Extreme Pressure Properties of Lubricating Fluids (Timken Method)</u>

Lubricant No. 4 (grade 10W) engine lubricant recorded the lowest average response with lubricant No. 3 (grade 85W-140) gear lubricant having the highest response (TABLE 6, Fig. 9). The lubricants fall in four average response groups. Lubricants Nos. 4 through 7 fall in the lowest average response group; also, their averages are significantly lower than those of lubricants Nos. 1, 2, 3, and 8. The lubricant No. 8 average is significantly lower than the average of lubricants Nos. 1, 2, and 3. Finally, lubricant No. 1 has a significantly lower average than lubricant No. 3.

4. <u>ASTM D 1947 Test Method for Load-Carrying Capacity of Fluid Gear Lubricants (Ryder Gear)</u>

Lubricants Nos. 1, 2, and 3 gear lubricants have the highest average response with lubricant No. 7 (grade 0W-20) Arctic engine lubricant having the lowest average response (TABLE 6, Fig. 10). The results fall into three average response groups. Lubricants Nos. 1, 2, and 3 fall into the highest average response group; their averages are significantly higher than those of the other lubricants. Lubricants Nos. 5, 6, and 8 fall into the second (middle) average response group. Lubricants Nos. 7 and 8 fall into the lowest average

response group, and their averages are significantly lower than those of the other lubricants.

5. Caterpillar TO-2 Friction Retention Test Method

Lubricant No. 8 (grade 85W-140) does not appear in the TO-2 test result because the lubricant could not complete the break-in cycle.

(i) Stop-Time Percent Increase: Lubricant No. 1 (grade 75W) gear lubricant had the highest average response (TABLE 6, Fig. 11). All seven lubricants had similar average responses.

(ii) Bronze Weight Loss: Lubricant No. 6 (grade 15W-40) engine lubricant had the lowest average response (TABLE 6, Fig. 12). All seven lubricants had similar average responses.

(iii) Steel Weight Loss: In addition to the bronze weight loss, lubricant No. 6 (grade 15W-40) engine lubricant also had the highest average response (TABLE 6, Fig. 13).

(iv) Total Wear: Lubricant No. 6 (grade 15W-40) engine lubricant recorded the lowest average response order, with all seven lubricants falling within the same average response group (TABLE 6, Fig. 14).

(v) Test Cycles: Engine lubricants Nos. 6, 7, and 8 recorded the largest average response with lubricant No. 1 (grade 75W) gear lubricant having the lowest average response (TABLE 6, Fig. 15). The lubricants fall into two average response groups. Engine lubricants Nos. 1 and 2 have significantly lower averages than lubricants Nos. 5, 7, and 8.

Numerical values of 1 = best through 8 = worst were assigned to each lubricant for each test based on the size of their average response. These values can be seen in TABLE 7. Gear lubricant No. 3 (grade 85W-140) ranked first in the ASTM D 2882 and ASTM D 2782 tests. The gear lubricant No. 2 (grade 80W-90) had the 1 = best result with ASTM D 4172

TABLE 7. Statistical Analysis Ranking

Test Specification	75W 1	80W-90 2	85W-140 3	10W 4	40 5	15W-40 6	0W-20 7	CD/50 8
	Lubricant Grade and Code Number							
ASTM D 2882								
Ring Wear	2	6	1*	7	4	8	5	3
Vane Wear	3	5	1	8	4	6	7	2
Total Wear	2	6	1	7	4	8	5	3
Rating Total	7	17	3	22	12	22	17	8
Statistical Ranking	2	5	1	7	4	7	5	3
ASTM D 4172								
Scar Diameter								
Statistical Ranking	5	1	3	8	6	7	2	4
ASTM D 2782								
OK Load Value								
Statistical Ranking	3	2	1	8	5	7	6	4
ASTM D 1947								
Load-Carrying Capacity								
Statistical Ranking	1	1	1	7	6	5	8	4
Caterpillar TO-2								
Stop-Time % Increase	7	3	8	6	4	5	1	2
Bronze Weight Loss	4	7	8	2	3	1	5	6
Steel Weight Loss	2	6	8	3	4	1	5	7
Total Wear	2	5	8	3	4	1	6	7
Test Cycles	7	6	8	5	1	4	1	1
Rating Total	22	27	40	19	16	12	18	23
Statistical Ranking	5	7	8	4	2	1	3	6
Statistical Total	17	16	14	34	23	27	24	21
Statistical Ranking	3	2	1	8	5	7	6	4

* 1 = Best; 8 = Worst.

test. Gear lubricants Nos. 1, 2, and 3 ranked 1 = best in the ASTM D 1947 test. The Caterpillar TO-2 test ranked the 15W-40 engine lubricant No. 6 as 1 = best.

The results based on the size of the average responses were used in a simple linear regression analysis to determine if the results from one test method could predict the results of any of the other tests. These results can be seen in TABLE 8. The only results that predict the results of the other tests are D 2872 and D 1947, which show a 0.885

TABLE 8. Simple Linear Regression Analysis Matrix of R-Squared Values

	D 4172 4-Ball	D 2872 Timken	D 1947 Ryder	D 2882 Vickers	D 4736 TO-2
D 4172 4-Ball	1.0	--	--	--	--
D 2782 Timken	0.26	1.0	--	--	--
D 1947 Ryder	0.09	0.885	1.0	--	--
D 2882 Vickers	0.02	0.31	0.22	1.0	--
D 4736 TO-2	0.04	0.41	0.29	0.20	1.0

correlation R-squared value. No other tests were able to predict the results of any other test with any validity as can be seen by their low R-squared values.

V. CONCLUSIONS

The ranks based on the size of the average response from the statistical analysis were compared to the ranks determined from the test procedure performance (see TABLE 9). The rankings were the same for the ASTM D 4172, D 2782, and D 1947 tests. The ASTM D 2882 test did not rank four of the lubricants the same. This response may be due to the fact that the test procedure uses only the total wear results for pass or fail performance. The statistical response data include the vane, ring, and total wear results. Nevertheless, the rankings were still similar.

The results of the Caterpillar TO-2 Friction test were not as good. The statistical results are based on the comparison of the size of the average responses, while the test procedure uses pass and fail limits that correspond to field data. Only the grade 0W-20 Arctic engine lubricant No. 7 passed all the specification requirements. As a result, it was ranked 1 = best; however, it ranked third in the statistical results. Statistically,

TABLE 9. Statistical Analysis Versus Test Procedure

Test Specification	75W 1	80W-90 2	85W-140 3	10W 4	40 5	15W-40 6	0W-20 7	CD/50 8
	Lubricant Grade and Code Number							
ASTM D 2882								
Statistical Ranking	2	5	1	7	4	7	5	3
Procedure Ranking	3	6	1	7	4	8	5	2
ASTM D 4172								
Statistical Ranking	5	1	3	8	6	7	2	4
Procedure Ranking	5	1	3	8	6	7	2	4
ASTM D 2782								
Statistical Ranking	3	2	1	8	5	7	6	4
Procedure Ranking	3	2	1	8	5	7	6	4
ASTM D 1947								
Statistical Ranking	1	1	1	7	6	5	8	4
Procedure Ranking	1	1	1	7	6	5	8	4
Caterpillar TO-2								
Statistical Ranking	5	7	8	4	2	1	3	6
Procedure Ranking	6	7	8	5	2	4	1	3
Total Ranking								
Statistical	17	16	14	34	23	27	24	21
Procedure	18	17	14	35	23	31	22	17
Overall Ranking								
Statistical	3	2	1	8	5	7	6	4
Procedure	4	2	1	8	6	7	5	2

lubricant No. 6 (grade 15W-40) was ranked as 1 = best, while the test procedure ranked it fourth.

After all the numerical rankings were totaled, the results were similar. The statistical analysis ranked the gear lubricants Nos. 1, 2, and 3 as the best. The five engine lubricants followed with lubricant No. 8 (grade CD/50) ranking best of the engine lubricants. The overall ranking of the test procedure also ranked gear lubricant No. 3 as best, but ranked engine lubricant No. 8 (grade CD/50) as a second place tie with lubricant No. 2 (grade 80W-90) gear lubricant. The correlation for the statistical and test procedure ranking can be seen graphically in Fig. 16. Even though gear lubricant No. 3 (grade 85W-140) was ranked best overall by both rankings, it should be remembered that this gear lubricant failed the Caterpillar TO-2 test and would have considerable problems in power-shift transmissions using bronze friction discs.

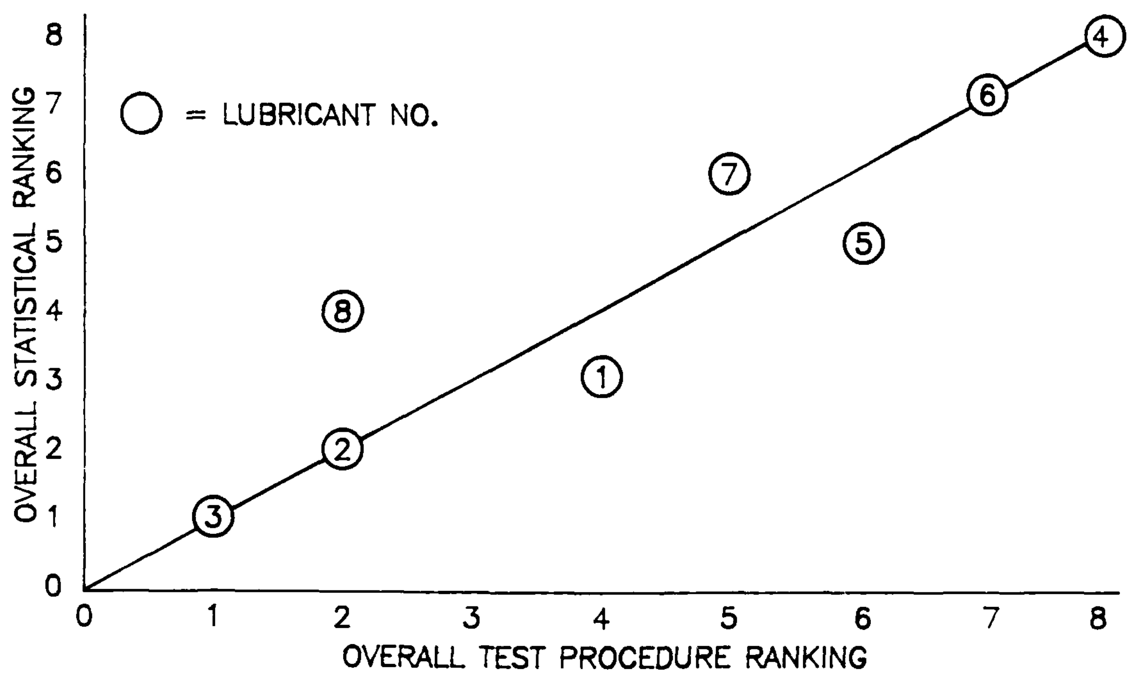

Figure 16. Correlation for the statistical and test procedure ranking

The use of the linear regression analysis correlation was able to predict the results of D 2872 and D 1947 test methods with approximately 89-percent accuracy, but was not able to predict the results of the other three test methods with sufficient accuracy.

The best overall performance with the least trade-off was selected from the friction and wear tests. This lubricant was engine lubricant No. 8, grade CD/50, MIL-L-2104C equivalent and could be used as a gear lubricant as could lubricant No. 5 (grade 40) engine lubricant but with more trade-offs.

VI. RECOMMENDATIONS

The results from this program show that the data are limited and that additional lubricant and test results are needed:

- Conduct the five friction and wear tests on at least 8 to 16 more lubricants.
- Conduct ICP elemental analysis on all lubricants.

VII. REFERENCES

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2. U.S. Military Specification MIL-L-2104D, Lubricating Oil, Internal Combustion Engine, Tactical Service, 1983.

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AMSTA-RGP (MR RAGGIO) 1
AMSTA-MLF (MR KELLER) 1
AMSTA-MC 1
AMSTA-MV 1
AMSTA-Z (MR FARKUS) 1
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CDR
US ARMY YUMA PROVING GROUND
ATTN: STEYP-MT-TL-M (MR DOEBBLER) 1
YUMA AZ 85364-9103

CDR
US ARMY GENERAL MATERIAL & PETROLEUM ACTIVITY
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STRGP-FE, BLDG 85-3 (MR GARY SMITH) 1
STRGP-FT (MR ROBERTS) 1
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US ARMY LABORATORY COMMAND
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AMSLC-TP-AL (LTC SCHRADER) 1
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CDR
US ARMY RES & STDZN GROUP (UK)
ATTN: AMXSN-UK-RA (DR REICHENBACH) 1
BOX 65
FPO NEW YORK 09510-1500

CDR
US ARMY TANK-AUTOMOTIVE CMD
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PM ABRAMS, ATTN: AMCPM-ABMS 1
PM BFVS, ATTN: AMCPM-BFVS 1
PM 113 FOV, ATTN: AMCPM-M113 1
PM M60 FOV, ATTN: AMCPM-M60 1
APEO SYSTEMS, ATTN: AMCPEO-CCU-S 1
PM LAV, ATTN: AMCPM-LA-E 1
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CDR
US ARMY RESEARCH OFFICE
ATTN: SLCRO-EG (DR MANN) 1
SLCRO-CB 1
P O BOX 12211
RSCH TRIANGLE PARK NC 27709-2211

PROGRAM EXECUTIVE OFFICE, TROOP SUPPORT
DEPUTY FOR SYSTEMS MGMT
ATTN: AMCEPO-TRP 1
ST LOUIS MO 63120-1798

CDR
US ARMY FOREIGN SCIENCE & TECH CENTER
ATTN: AIAST-RA-ST3 (MR BUSI) 1
FEDERAL BLDG
CHARLOTTESVILLE VA 22901

CDR
US ARMY TANK-AUTOMOTIVE CMD
PROGR EXEC OFF COMBAT SUPPORT
PM LIGHT TACTICAL VEHICLES
ATTN: AMCPM-TVL 1
PM MEDIUM TACTICAL VEHICLES
ATTN: AMCPM-TVM 1
PM HEAVY TACTICAL VEHICLES
ATTN: AMCPM-TVH 1
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CDR, US ARMY TROOP SUPPORT COMMAND
ATTN: AMSTR-ME 1
AMSTR-S 1
AMSTR-E (MR CHRISTENSEN) 1
AMSTR-WL 1
4300 GOODFELLOW BLVD
ST LOUIS MO 63120-1798

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US ARMY GENERAL MATERIAL & PETROLEUM ACTIVITY
ATTN: STRGP-PW 1
BLDG 247, DEFENSE DEPOT TRACY
TRACY CA 95376-5051

PROJECT MANAGER
PETROLEUM & WATER LOGISTICS
ATTN: AMCPM-PWL 1
4300 GOODFELLOW BLVD
ST LOUIS MO 63120-1798

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US ARMY MATERIALS TECHNOLOGY LABORATORY
ATTN: SLCMT-M 1
SLCMT-MCM-P (DR FOPIANO) 1
WATERTOWN MA 02172-2796

DEPARTMENT OF THE NAVY

CDR
NAVAL AIR PROPULSION CENTER
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PE-32 (MR MANGIONE) 1
P O BOX 7176
TRENTON NJ 06828-0176

CDR
NAVAL SEA SYSTEMS COMMAND
ATTN: CODE 05M32 1
WASHINGTON DC 20362-5101

JOINT OIL ANALYSIS PROGRAM - TECHNICAL SUPPORT CTR 1
BLDG 780
NAVAL AIR STATION
PENSACOLA FL 32508-5300

CDR
DAVID TAYLOR RESEARCH CTR
ATTN: CODE 2830 (MR SINGERMAN) 1
CODE 2831 1
ANNAPOLIS MD 21402-5067

CDR
NAVAL AIR DEVELOPMENT CTR
ATTN: CODE 6061 1
WARMINSTER PA 18974-5000

CDR
NAVAL RESEARCH LABORATORY
ATTN: CODE 6170 1
CODE 6180 1
WASHINGTON DC 20375-5000

OFFICE OF THE CHIEF OF NAVAL RESEARCH
ATTN: OCNR-126 (DR ROBERTS) 1
ARLINGTON VA 22217-5000

DEPARTMENT OF THE AIR FORCE

CDR
US AIR FORCE WRIGHT AERO LAB
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AFWAL/MLBT (MR SNYDER) 1
WRIGHT-PATTERSON AFB OH
45433-6563

CDR
SAN ANTONIO AIR LOGISTICS CTR
ATTN: SAALC/SFT (MR MAKRIS) 1
SAALC/MMPRR 1
KELLY AIR FORCE BASE TX 78241

OTHER GOVERNMENT AGENCIES

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NATIONAL INSTITUTE FOR PETROLEUM AND ENERGY RESEARCH PO BOX 2128 BARTLESVILLE OK 74005	1